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Dissertation Abstract

Spin-Dependent Transport in Ferromagnet/Narrow-Gap Semiconductor Two-Dimensional Electron Gas Systems

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Recently, study of semiconductor spintronics that explore the possibility of new functional devices based on new principles or materials using both the charge and spin in semiconductors has been actively carried out. In particular, spintronics for the nonmagnetic semiconductor (NMS) based materials have attracted much attention owing to their high adaptability to the existing device fabrication techniques. The first proposed active device in NMS-spintronics is Datta-Das type spin field-effect transistor (spin-FET). The most prominent problem in realization of the spin-FET is the high-efficiency electrical spin injection into a two-dimensional electron gas (2DEG) showing strong Rashba spin-orbit coupling (RSOC) from ferromagnetic electrodes. Previously, evaluation of the pure spin injection effect was almost impossible due to the current magnetoresistance effect of ferromagnet (FM) and the very low spin injection efficiency. Thus, detailed knowledge of the behavior of the spin current injected into narrow-gap semiconductor (NGS)-2DEG was not obtained. In this study, investigations comparing the nonlocal spin-valve (NLSV) and weak-antilocalization (WAL) were carried out to obtain the detailed knowledge related to spin transport properties in NGS-2DEG. The NGS-2DEG wafer used in this study is an InGaAs/InAlAs inverted heterostructure with 75 %-In-content. The InGaAs-2DEG channel was grown on a semi-insulating GaAs(001) substrate via $\mathrm{In}_x\mathrm{Al}_{1-x}\mathrm{As}$ ($x = 0.15$–0.8, $\Delta x = 0.05$, 100 nm/step) metamorphic step graded buffer layers by conventional solid-source molecular beam epitaxy. Si delta-doping layer is located at the substrate side from the InGaAs-2DEG channel with no doping nor barrier layers between the surface and the 2DEG interface. Also, since the In content is high, Schottky barrier height is anticipated to be up to $\sim$ 20 meV for realization of a high-efficiency barrierless spin injection. Hall-bar and lateral SV (LSV) devices were fabricated on a single InGaAs-2DEG wafer. The FM electrodes of LSV devices are CoFe alloy, which is expected for high-spin polarization.

First of all, the basic characteristics of InGaAs-2DEG wafer were evaluated using the Hall-bar devices. The 2DEG was confirmed through observation of quantum Hall effect under the high magnetic field region at 1.6 K. As a result of magnetoresistance measurements, negative magnetoresistance at neighborhood of zero magnetic field is observed, i.e., weak-antilocalization. As a result of an analysis using the assumed D'yakonov-Perel' (DP) spin relaxation mechanism for the WAL, RSOC constant showing strength of RSOC is estimated to be $\sim 5.1 \times 10^{-12}$ eV $\cdot$ m. In addition, the spin-orbit relaxation length determined by the RSOC constant and the electron effective mass was estimated to be ~ 0.6 μm.

Next, NLSV characteristics of the LSV device were evaluated at 1.6 K. Hysteresis of the non-local resistance dips was observed in the vicinity of $\sim \pm 40$ mT. In the three-terminal resistance including the FM of magnetoresistance, anisotropic magnetoresistance (AMR) is observed. From the comparison of the NL-resistance and AMR, NL-resistance dips were observed in anti-parallel alignment status of the magnetization of the FM. From the above results, a successful electrical spin injection into an InGaAs-2DEG from FM was confirmed. Additionally, magnitude of the NL-resistance change seems to decay exponentially with increase in the FM electrode spacing. This is a typical behavior of pure spin currents. As a result of an analysis using one-dimensional drift-diffusion model, spin diffusion length and spin polarization at CoFe/InGaAs interface were estimated to be ~ 5.1 μm and ~ 5.7 %, respectively. If the spin polarization of the CoFe electrode is assumed to be less than 55 %, spin injection efficiency is estimated to be higher than 11 %. The spin diffusion length and the spin polarization are three times as high as those of the FM/InAs-2DEG system reported by other groups. On the other hand, the ratio of the spin-orbit relaxation length and spin diffusion length is ~ 8.5. The same physical phenomena is not necessarily observed in both cases, indicating the possibility of different spin relaxation mechanisms.

These results are important findings in realization of the spin-FETs, and therefore, the NMS-spintronics.

Keywords: narrow-gap semiconductor, two-dimensional electron gas, Rashba spin-orbit coupling, nonlocal spin injection